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Abstract. Vibration induced from road surface has an impact on the durability and reliability of electrical and mechanical components attached on the vehicle. There is little research published relevant to the durability assessment of a flywheel energy recovery system installed on city and district buses. Relevant international standards and legislations were reviewed and large discrepancy was found among them, in addition, there are no standards exclusively developed for kinetic energy recovery systems on vehicles. This paper describes the experimentation of assessment of road surface vibration input to the flywheel on a bus as obtained at the MIRA Proving Ground. Power density spectra have been developed based on the raw data obtained during the experimentation. Validation of this model will be carried out using accelerated life time tests that will be carried out on a shaker rig using an accumulated profile based on the theory of fatigue damage equivalence in time and frequency domain aligned with the model predictions.

1. Introduction

In recent years, the automotive and road transport sector is paying more attention to developing technologies for reduction of vehicle energy consumption and emission of carbon dioxide (CO2), which is a major source of the greenhouse effect on our planet [1]. Therefore, this is the motivation for vehicle manufacturers and subsystem suppliers to develop innovative energy saving products, such as electric vehicle and hybrid electric vehicle [2]. Within this area, one of the main innovative technology is designed, integration and implementation of an energy recovery system for different types of vehicles [3]. Recently, an innovative hybrid flywheel energy storage system (FESS) has been developed by GKN Hybrid Power [4]. This technology is using a kinetic energy recovery system to harvest the energy lost (during the vehicle brake) as heat, which is stored in the flywheel and re-powered to wheel when necessary. Therefore, this flywheel system is ideal for city buses due to their high start-stop frequency under busy urban road environment.

In order to maintain the capability of continuous energy saving and high quality performance of this flywheel system, it is necessary to investigate the robustness and durability of FESS. There is little published research relating to the examination of the flywheel system experience during its service on the bus. In addition, there is no international standard and legislation relating to the investigation of vibration input to FESS operating in urban public transport. Most of existing standards are designed for components, such as batteries, on a general vehicle and do not consider the type of vehicle. A major cause of durability failure of electric component of the vehicle is due to the impact of vibration induced by the road surface [5]. Consequently, it is necessary for design engineer to understand the frequency and severity of vibration input that FESS will be exposed during its service life.

The current study is focused on the assessment of durability requirement for the flywheel system operating on an urban bus. After a comprehensive review of the relevant standards and legislations, the experimentation on a two double Decker bus on Pave road is presented in order to formulate a test profile, which emulates total vibration that FESS exposed during designed life time 15 years. The contribution of this work is a guidance for issuing a further standard or legislation for vibration input to the component used for urban bus.

The structure of this paper is summarised below. Some relevant standards and legislation are reviewed with explanation of their drawbacks and limitation for the current study in Section 2. In Section 3, the experimentation is presented in details to illustrate the methodology and how to derive an accelerated life test specification. The results of the derived profile are shown in Section 4. The final section is the conclusion of this study.

2. Review of relevant standards and related published research

Although there is no standard exclusively for FESS used on the bus, some standards and regulation for electrical component used on different types of vehicle are valuable references for comparison, which are generally issued by the appropriate recognised organisation and can be implemented by vehicle manufacturers and subsystem supplier. It is also important to note that there is legal requirement for manufacturers to meet the relevant standard or legislation for their customers. However, there are clear differences between these standards and legislations, therefore the aim of this section is to critically evaluate their test specification in order to identify the merits and drawbacks for assessment of the durability of FESS on a bus. In addition, published paper regarding to this topic are also mentioned in this section.

2.1. ISO 16750

The international standard ISO16750 is to guide the user to define or specify test requirement, which are based on the actual environment in which the unit under test will be exposed to during its life cycle [6]. The unit under test in this standard is electrical and electronic equipment on road vehicle.

This standard is developed by considering several environmental factors, including geography & climate, vehicle use condition & operating modes, types of vehicle and equipment location. Road vehicles operate in most land regions of our planet. There are different influences on these vehicles when running in different places around the world. In addition, significant variation in climate such as seasonal cycles can impact the environmental condition that vehicle exposed to. Environmental conditions depend on road quality such as the type of road surface, vehicle usage (e.g. commuting, towing, cargo transport, etc.) In addition, operating modes including storage, starting, driving, stopping has been considered in generating this standard. Consideration has also been given to different types of vehicles such as commercial vehicles, passenger cars with different engines (gasoline and diesel). Environmental conditions depend on engine size, suspension characteristics, mass and size of the vehicle, etc. The environmental condition also depends on the equipment mounting location due to different location on the vehicle has its specific environmental loads. For example, temperature range of the components near or on engine differs significantly from the temperature range in the passenger compartment. It is also the similar as types of vibration loads on different component on the vehicle. Body mounted components are mainly experienced random vibration condition, while for engine mounted component, there is additional periodical sine vibration generated by the engine, which must be considered.

The power spectrum density profiles are shown in Part 3 of ISO 16750 according to different types of vehicles (passenger car or commercial vehicle) and different locations e.g. near the engine, gearbox or sprung mass. However, one limitation of this standard is that there is no information about the profile can be used on which axis of the vehicle, vertical, longitudinal or lateral direction. In addition, the classification of vehicle types does not include urban operating bus. To sum up, this standard is not suitable for current study.

2.2. SAE 2380

This Standard includes three independent profiles that can be used to complete the whole test [7]. This standard is used for obtaining a test profile for assessment of vibration generated by road surface to electric vehicle batteries, which play a similar role in the vehicle as the power source. The test profile in this standard was derived based on the actual data generated during road testing and can be emulated to a 100,000 miles distance. It is noteworthy that there is no information regarding to the data was gathered from what type of vehicle, such as a passenger car or a commercial bus, etc. The duration of the test profiles was compressed within a period of time between 13.6 hours and 92.6 hours.

There are three points worthnoted when relating to this standard. In the first, the vibration levels of longitude and transverse direction are treated the same in SAE J2380. Although this assumption would clear make the durability test easier, there is no evidence to validate this condition. Secondly, the random vibration range used in the profile is between 10 Hz and 190 Hz, which is similar to the previous work done by Martin et al [8]. Arguably, there is no evidence that the frequency range below 5 Hz and above 190 Hz do not contribute to the vibration impact to the components on vehicles. The final point to mention is that there is no vehicle type classification, which is an important impact factor to the vibration level that component experiences on different vehicles.

2.3. ECE Regulation 100

The aim of this regulation is to verificate the durability and safety of energy storage system such as a battery that used on vehicle [9]. The frequency range in the vibration profile is between 7 Hz and 50 Hz. The duration of each load cycle 15 minutes and total 12 times repeat will last for 3 hours for the testing in the vertical axis direction of the battery system [9]. There is no definitely pass or fail criteria in this standard rather than defining the battery has to be observed for 1 hour under room temperature after finishing the vibration profile.

There is little information for the manufacturers of the battery system to determine the durability of their products. In addition, there is also limited scope of the standard that can be used to determine the expected lifetime. Arguably, ECE Regulation 100 mainly focuses on the short duration testing of the battery system. The additional drawback of this standard is that it only tests the system in the vertical axis direction, and does not relate to the vibration on horizontal directions in the vehicle.

2.4. Regulation UN38.3

This regulation is a legal requirement regarding the delivery of electric battery systems [10]. It includes the vibration test profile that can be used to emulate the vibration level that systems during air transportation. The test process is reviewed and presented in the regulation with demonstrating the force level and frequency range that the system may experience. Eventually, there must be no weight reduction, venting, leakage during or after the test of battery systems to meet this legislation.

There are also some concerns claimed by a number of vehicle manufacturers and battery system supplier for the application of this regulation [10]. This regulation mainly focuses on the worst case vibration and shock scenarios and the profiles in this regulation are not representing the components experience during vehicle operation on the road. Therefore, it is concluded that Regulation UN38.3 is not appropriate for assessing the vibration levels in-vehicle service life of the flywheel.

2.5. Related published research

There has been very little published, peer-reviewed paper relevant to the durability test of flywheel energy storage system used on buses. Some papers contributed the area of durability test of battery system used on the vehicle are interested to be reviewed. Martin et al. obtained a vibration profile for the electric battery used on small passenger cars, which was driven on a range of different road surfaces (such as urban road, pave road, motorway etc.) with tri-axial accelerometers are fixed on the B-pillar of the vehicle [8]. The shock event was also included in their study by traversing a series of speed bumps. Based on the actual data, power spectrum density profiles were derived during the frequency range between 7Hz to 150Hz. The peak value of power density is 0.48 g^2Hz^{-1} in vertical (Z) axis and observed during the frequency range of 10 Hz to 20 Hz. In the horizontal directions, both X and Y axis was found to peak at 0.063 g^2Hz^{-1} at 15Hz. Hooper and Marco [11] described their work about assessment of vibration input to electric battery installed on electric vehicles. Three electric vehicles – Nissan Leaf, Smart ED and Mitsubishi iMiEV- were driven on the Millbrook Proving Ground to generate the vibration power spectrum density used for durability test. Six tri-axial accelerometers were placed at different locations on the vehicle to record the data when operating on different road surfaces. Eventually, a test profile was derived to emulate the vibration level that represents 100,000 mile vehicle life.

3. Experimentation
Due to the inconsistency as to the standards and legislation discussed above, it is necessary to assess the vibration input to the flywheel used on bus. Therefore, the aim of this section is to present the experimental measurement of vibration load on the commercial urban bus, which will be equipped with flywheel to add the energy recovery function during the operation. The road data is recorded directly on the MIRA proving ground on Pave road surfaces.

3.1. Vehicle and equipment
The vibration data are measured on a two decker urban bus, which is used on the MIRA Proving Ground in order to develop a bus durability test profile. The specification of test vehicle is listed in Table 1. The test events are classified at two conditions, minimum test weight (only driver on-board) and maximum weight capacity (full passengers) in order to cover the total range of vibration level.

Table 1. Test bus parameter.

Vehicle	
Vehicle Make	Wrightbus Ltd
Model	AA531
Chassis Number	Volvo 89TL
Body Length	10,404mm
Body Width	2,520mm
Minimum Test Mass	12,100 kg
Maximum Test Mass	17,918 kg

The bus is mounted with 3 accelerometers on the location behind the front left wheel, which is the location used for mounting the flywheel. The record amplitude of accelerometers is 100g. Apart from the vibration data recorded through accelerometers, the engine speed and vehicle velocity are also recorded by using a SIRIUS multi-channel data acquisition system. The data were collected at a sampling rate of 5000 Hz, according to the Nyquist sampling theorem, band limit from 0 Hz to half sample rate (2500 Hz) is suitable for the vibration characterisation of vibration input due to the frequency range in all relevant standards are below 1000Hz. The data recorder is shown in figure 1.

The vibration measurement was recorded by driving the bus on a pave road surface on MIRA Proving Ground, UK. The pave surface is a type of urban road that used for evaluating a vehicles Noise, Vibration & Harshness (NVH) and durability. Detailed information can be found on the website of MIRA.

Figure 1. Sirius data acquisition system used for measuring the acceleration at locations on the bus where the kinetic energy recovery system may be installed.

3.2. Derivation of vibration profiles for lab test

When the pave road data were obtained during the test, accelerated life test is used to apply higher stress than it on the Pave road in order to finish the durability test of flywheel quickly and conveniently. Therefore, the conversion from Pave road data to laboratory shaker rig test is achieved under the theory of fatigue damage equivalence in time and frequency domain. In details, the Fast Fourier Transformation technique is to convert the time domain data to the frequency domain. The test duration is accelerated based on Miner Hyposis in equation (1).

$$\frac{t_2}{t_1} = (\frac{Grms_1}{Grms_2})^m \tag{1}$$

where t_1 life equivelated duration on pave road.

$Grms_1$ is vibration severity on pave road.

$Grms_2$ and t_2 are are vibration severity on shaker rig and duration of testing on shaker rig.

m is a value based on the slope of S-N (stress amplitude – Number of cycles) curve for the appropriate material. This value is based on the most critical material in the flywheel system, the rotor, which is made of carbon fibre. The S-N curve is shown in figure 2 and m value can be worked out at 4.

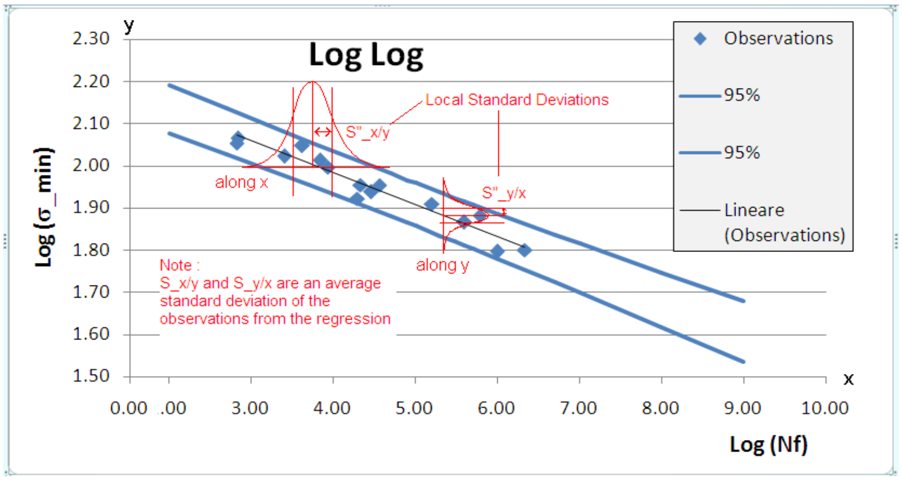

Figure 2. Stress – number of cycle fatigue (S-N) curve of flywheel rotor.

4. Results and discussions

During the measurement, the real vibration inputs into the vehicle are recorded at the location where the flywheel equipped on bus. Figure 3 shows the raw data of acceleration vs time under minimum weight condition running on proving ground. This raw data was analysis by FFT method in order to obtain frequency domain information. The Hamming window method is applied in Matlab software and PSD profile is shown in figure 4.

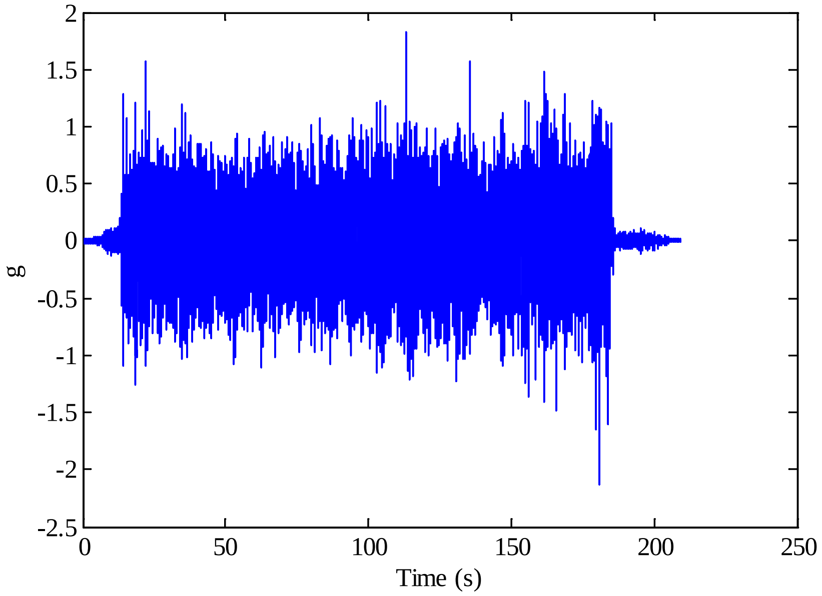

Figure 3. Measured acceleration on pave road in the vertical direction.

It is clear in figure 4 that there is still high level vibration at 5 Hz, however, in the standards mentioned in Section 2, the minimum vibration level is 7 or 10 Hz. Based on this result, it is necessary to reduce the frequency range to 5 Hz or lower. The vibration below 5 Hz is important, however, due to the limitation of shaker rig default range used in a lab test, the minimum frequency should not be lower than 5Hz in the durability testing with available facility. In addition, the vibration level beyond 200 Hz is only 10^{-6} g^2/Hz or smaller, there is no need to consider such small vibration impact on the flywheel on the bus. Therefore, the frequency range is set from 5 Hz to 200 Hz.

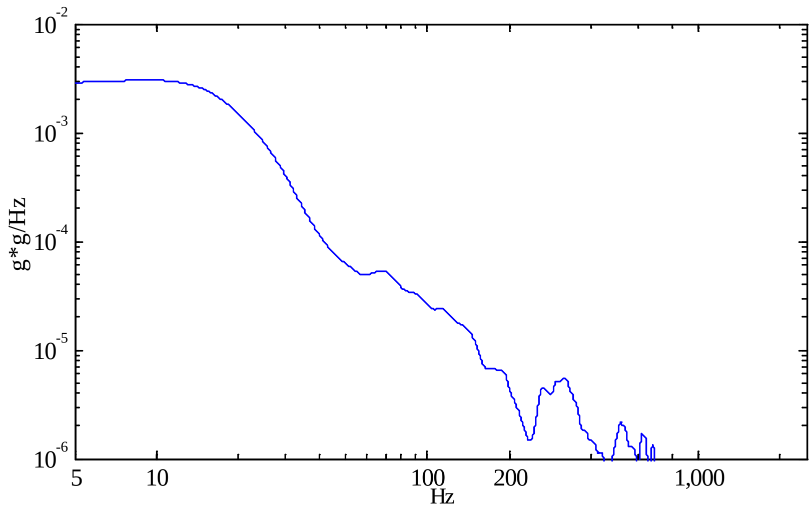

Figure 4. Frequency response function obtained by applying the Fast Fourier Transform (FFT).

The flywheel life time is designed for 15 years on the bus, which will operate 750,000 miles totally. On MIRA Proving Ground, 1 mile proving ground equivalents to 75 mile urban road surface, which means the bus will run on the pave road surface for 10,000 miles equals to the whole life vibration exposed on the urban surface road. The vehicle speed on the pave road testing is 20 mile/hour. Therefore, the test duration for the PSD profile in figure 4 is 500 hours, which is quite time consuming and costly. It is necessary to squeeze the time duration by accelerated life test. In the current study, the increased stress method by increased the vibration level in the same frequency range is applied based on Miner Fatigue Equivalent Hypothesis in equation (1). The PSD profile in figure 4 is smoothed to the blue line in figure 5. The Grms of pave road can be calculated at 0.67 g. In order to reduce the laboratory test duration, the Grms is enhanced to 1.35g (Red line in Figure 5). The power factor m is set at 4 due to this value is considered the most critical component in the flywheel system. Therefore, the total test duration of shaker rig test is 31.25 hours.

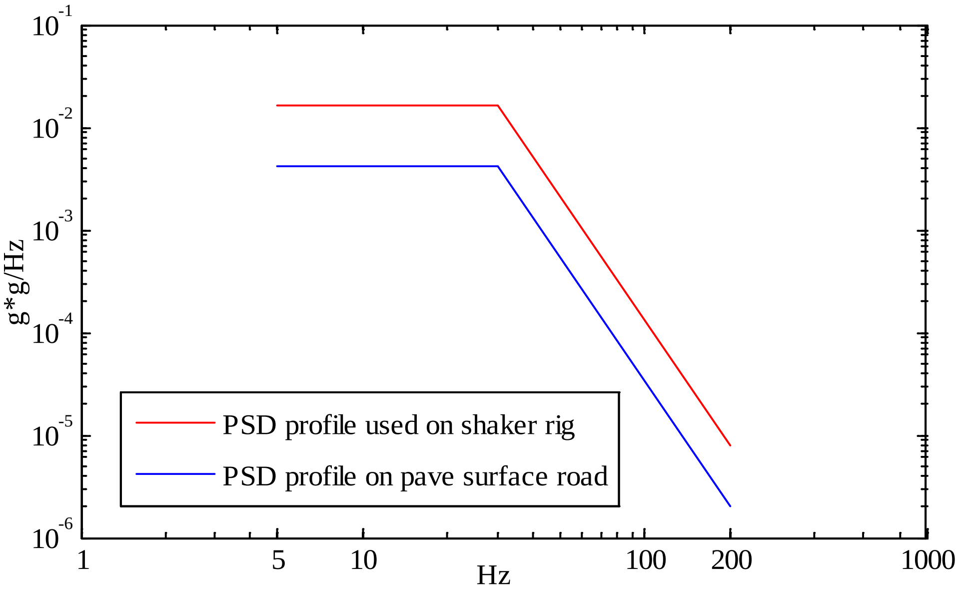

Figure 5. Smoothed Power Spectral Density (PSD) profile of pave road and lab test.

The test was under two conditions of minimum and maximum weight capacity and the results are shown in figure 6 that the vibration level at minimum weight (no passenger) is obviously higher than the maximum weight bus(full passengers). Therefore, the most critical condition at minimum weight is used in the equation (1).

The accelerated life test profile is compared to ISO 16750 and SAE J2380 in figure 7. There are clear differences between the actual derived profile and standards. Due to there is high value in vibration from the road surface under 10Hz base on the ground testing, it is necessary to lower the start of the PSD profile from 5Hz. In addition, the vibration level in the range of the frequency above 200 Hz is lower than 10^{-3}g, therefore it is not necessary to consider the vibration input above 200Hz. The large discrepancy among them indicates that Standard SAE J2380 and ISO 16750 are not suitable for the durability test of mechanical system used on the bus. More over, SAE J2380 and ISO 16750 are not issued for the durablity test of components on a urban bus. The PSD profile derived from actual ground testing can be used on further lab accelerated lifetime testing on a shaker rig.

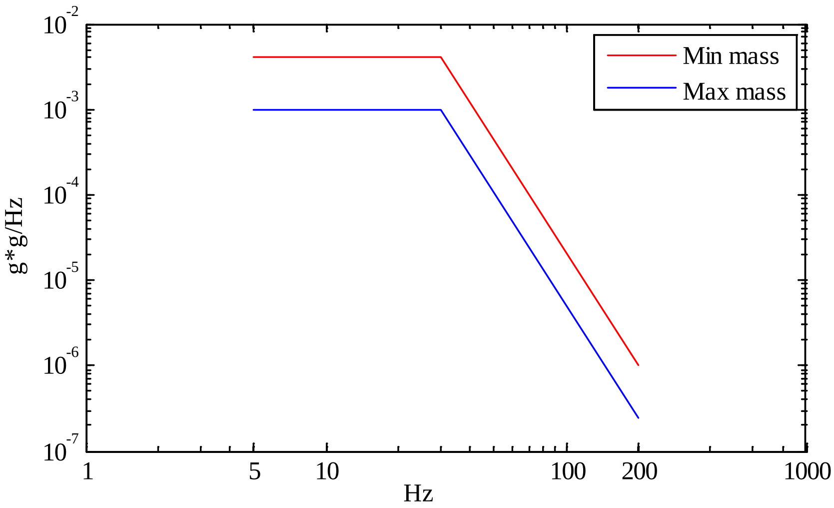

Figure 6. Calculated Power Spectral Density (PSD) profile for a different mass of the bus.

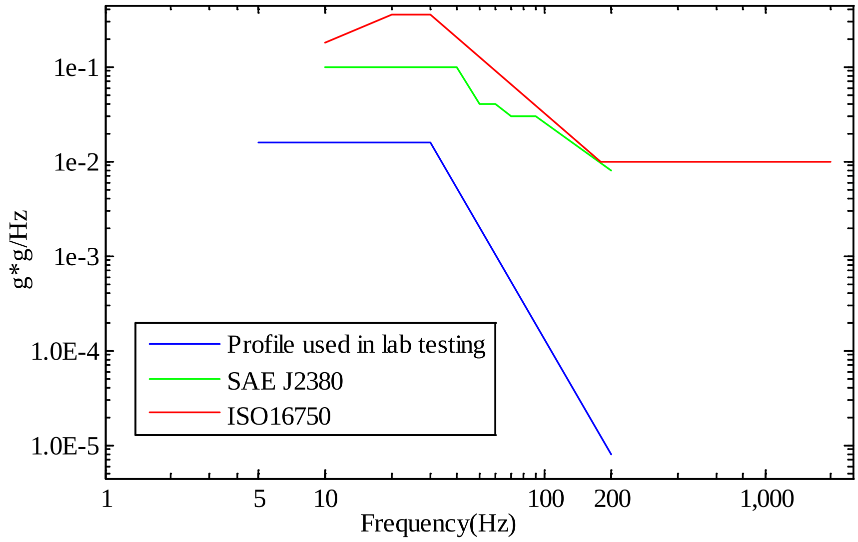

Figure 7. Comparison between the profile used on the shaker rig and the ones prescribed in ISO16750 and SAE J2380.

5. Conclusion and future work

Field or lab durability tests are used to validate and verify a product's reliability. The test specifications employed are usually based on International Standards or on the existing know-how in each company. For mechanical kinetic energy recovery systems installed on buses, there is no relevant standard for durability test in a laboratory. A comprehensive review of different standards and legislation relevant to the durability test of equipment on different vehicle is carried out followed by experimentation on MIRA's Proving Ground. The acquired data are utilized to develop a lab test specification on shaker rig based on the fatigue equivalence theory. This study fills the blank in this area and contributes to the generation of international standard for kinetic energy recovery components used on buses. Future work will be using this PSD profile to carry out the accelerated life time testing of the flywheel system on a shaker rig.

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